

A DISRUPTED CIRCUMSTELLAR TORUS INSIDE ETA CARINAE'S HOMUNCULUS NEBULA¹

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ABSTRACT

We present thermal infrared images of the bipolar nebula surrounding η Carinae at six wavelengths from 4.8 to 24.5 μm . These were obtained with the MIRAC3 camera system at the Magellan Observatory. Our images reveal new intricate structure in the bright core of the nebula, allowing us to re-evaluate interpretations of morphology seen in images with lower resolution. Complex structures in the core might not arise from a pair of overlapping rings or a cool (110 K) and very massive dust torus, as has been suggested recently. Instead, it seems more likely that the arcs and compact knots comprise a warm (~ 350 K) disrupted torus at the intersection of the larger polar lobes. Some of the arcs appear to break out of the inner core region, and may be associated with equatorial features seen in optical images. The torus could have been disrupted by a post-eruption stellar wind, or by ejecta from the Great Eruption itself if the torus existed before that event. Kinematic data are required to rule out either possibility.

Subject headings: circumstellar matter — ISM: individual (Homunculus Nebula) — stars: individual (η Carinae)

1. INTRODUCTION

An elegant expanding bipolar nebula known as the Homunculus surrounds the persistently peculiar star η Carinae. The nebula contains several M_{\odot} of material, most of which was ejected during a major eruption about 160 years ago (see Davidson & Humphreys 1997). *Hubble Space Telescope (HST)* images at optical wavelengths (Morse et al. 1998) show interesting detailed structure in the polar lobes, as well as a ragged equatorial debris disk. Dust in the Homunculus absorbs most of the star's UV and optical flux, and then re-emits roughly $4 \times 10^6 L_{\odot}$ at infrared (IR) wavelengths, making η Car one of the brightest sources in the sky at 10 μm (Westphal & Neugebauer 1969), despite its distance of 2.3 kpc (Davidson & Humphreys 1997). IR radiation is an especially useful way to study η Car because it reveals structures *inside* the Homunculus

¹Based on observations made at the Baade Telescope of the Magellan Observatory, a joint facility of The Carnegie Observatories, Harvard University, Massachusetts Institute of Technology, University of Arizona, and University of Michigan.

that are mostly obscured at shorter wavelengths. Numerous investigations at IR wavelengths have shown a bright, elongated, and multiple-peaked core a few arcseconds across (e.g., Hyland et al. 1979; Mitchell et al. 1983; Hackwell et al. 1986; C.H. Smith et al. 1995; Rigaut & Gehring 1995; Smith et al. 1998; Polomski et al. 1999; Smith & Gehrz 2000). These features are usually interpreted as an inclined and limb-brightened circumstellar torus or disk. The sharpest mid-IR image of η Car so far was presented by C.H. Smith et al. (1995), who used a special processing technique to produce a remarkable $12.5\ \mu\text{m}$ image showing the detailed spatial structure of the core, consisting of several knots and loop structures. Smith et al. (1998) and Polomski et al. (1999) discussed multi-wavelength IR array images of η Car, and summarized this object’s unique thermal-IR emission properties.

A controversy has recently arisen regarding the nature of the bright structures in the core of the Homunculus. Several previous observers had described the torus and showed that it had a color temperature higher than 250 K at wavelengths near $10\ \mu\text{m}$ (e.g., Hackwell et al. 1986; C.H. Smith et al. 1995; Smith et al. 1998; Polomski et al. 1999). However, Morris et al. (1999) recently claimed to have discovered this feature, and their interpretation of a large-aperture 2 to $200\ \mu\text{m}$ spectrum obtained with the *Infrared Space Observatory* (*ISO*) led them to associate the torus with much cooler dust at 110 K. They proposed that this cool torus contained $15\ M_{\odot}$ of material, and was formed when a companion star in a close binary system stripped the normal composition envelope off the primary star before the Great Eruption. They further suggested that the ejection of this massive torus caused the Great Eruption (by increasing the star’s L/M ratio) and was directly responsible for the bipolar shape of the Homunculus Nebula. However, Davidson & Smith (2000) showed that the hypothesized compact torus inside the Homunculus would be too small to radiate the required luminosity with a brightness temperature of only 110 K. Hony et al. (2001) proposed instead that the inner dust was warmer, as already shown by earlier studies, but they interpreted structure seen in their images as a pair of overlapping rings with a geometry analogous to those around SN 1987a (e.g., Burrows et al. 1995). These hypothetical rings have a different polar axis than the Homunculus — so Hony et al. (2001) made the extraordinary claim that an interaction between three bodies had caused the orbital axis to change orientation by more than one radian during or after the Great Eruption in the mid-19th century when the Homunculus was ejected. This interpretation seems unlikely for several reasons, and here we present new IR data showing that interpreting the IR features inside the Homunculus as a pair of rings is less straightforward than Hony et al. suggest. Instead these features could comprise an equatorial disk of material as previously proposed, which appears significantly disrupted when observed at high spatial resolution.

In §2 we present our new thermal-IR images, and in §3 we discuss the IR structures observed in these high-resolution images, as well as their consequences for previous interpretations of η Car’s IR radiation. This will be a brief and descriptive analysis of the IR structures in the core of the nebula; a more thorough quantitative analysis of these data will follow in a later paper.

2. OBSERVATIONS

Thermal-IR images of η Carinae were obtained on 2001 August 8 with the MIRAC3/BLINC instrument mounted on the Baade 6.5m telescope of the new Magellan Observatory. The images presented here were among the first thermal-IR data obtained with the Magellan telescopes. MIRAC3 is a mid-IR array camera built for ground-based astronomical imaging at Steward Observatory, University of Arizona, and the Harvard-Smithsonian Center for Astrophysics (Hoffmann et al. 1998). It utilizes a Rockwell HF-16 128×128 hybrid BIB array, and is an upgrade from the original MIRAC system (Hoffmann et al. 1994). Standard chop-nod

sets of images were obtained using six narrow filters at the wavelengths listed in Table 1, which summarizes other observational parameters.

The new images have better spatial resolution than any previous images of η Car at these wavelengths, and reveal new and important structures. However, η Car was observed primarily as a test of MIRAC3’s image quality on the new Baade 6.5m telescope, and so proper observations for flux calibration before and after each observation were not performed. The standard star γ Cru was observed just after η Car on the same date at 4.8 and 18.0 μm , but the only acceptable calibration observations at remaining wavelengths were obtained a few nights later on 2001 August 14, using HD 169916 as the standard star. The 18.0 μm filter was used on both occasions, and the resulting calibration for the two observations agreed to within 10%. Despite these difficulties, the resulting *relative* fluxes between various filters agreed with those expected from the *ISO* spectrum of η Car published by Morris et al. (1999), so the data are useful for investigating spatial variation in color temperature and other emission properties of the dust. The relative photometric accuracy is $\sim 10\%$, mainly due to uncertainty in the calibration system.

After sky subtraction, airmass correction, and gain correction, individual frames were combined with pixels subdivided by a factor of 2, for a final pixel scale of $0''.061$. Numerous frames were obtained for each filter, which allowed us to reject those with unsatisfactory seeing or focus. False-color representations of the final images in each of the six MIRAC3 filters are shown in Figure 1.

Only the 10.3 μm filter is severely affected by emission from silicates, so we can use the other filters to estimate the grain color temperature and emission opacity at each position in the nebula, after applying small corrections for wavelength-dependent spatial resolution (see Table 1). Figure 2a shows a map of the 12.5 to 18.0 μm color temperature distribution, and the corresponding 18 μm emission optical depth is shown in Figure 2b. These maps were constructed using methods that are standard for mid-IR array imaging (for instance, Polonski et al. 1999 explain how to derive T_c and τ maps). We assumed that the grains have an emissivity proportional to λ^{-1} , appropriate for amorphous silicates with $a \approx 1 \mu\text{m}$.

3. MORPHOLOGY OF THE BRIGHT INFRARED CORE

The diffraction limit of the Magellan I telescope’s 6.5m primary mirror has allowed us to produce high-quality IR images of the Homunculus Nebula without using extensive image enhancement routines. The images in Figure 1 give a much sharper picture of structures near the star seen previously in the 10 to 20 μm continuum (C.H. Smith et al. 1995; Hony et al. 2001), the near-IR continuum (Rigaut & Gehring 1995; Smith & Gehrz 2000), and near-IR Br γ emission (Smith et al. 1998).

Several compact knots reside in the core; the best example is the bright spot $\sim 1''$ SE of the star in the 8.8 μm image in Figure 1b. These knots could be part of an equatorial torus, but if so, they are not equidistant from the star (the hypothetical torus has some azimuthal asymmetry). Figure 2 suggests that, in general, the bright spots are found at the warm heads of protruding regions of relatively high density. The brightest knot, located less than $0''.5$ to the NW of the star, coincides with compact *equatorial* emission-line blobs seen in high-resolution optical studies (Hofmann & Weigelt 1988; Davidson et al. 1995).

Thin filaments that form arcs or loops appear to connect adjacent IR knots in the core. In some directions these features appear to break through the constraining dust torus (extended features are seen best at 18 and 24.5 μm), and coincide with prominent equatorial features in optical *HST* images (see Morse et al. 1998). However, the relationship between the IR (thermal dust emission) and optical (scattered light)

structures is unclear. These arcs resemble some remarkable features seen recently in *HST* images of the red supergiant VY CMa (Smith et al. 2001a). The prominent arc $2''$ SE of the star clearly connects with the limb-brightened rear wall of the receding polar lobe in the 18 and $24.5\ \mu\text{m}$ images. In fact, the dust optical-depth map in Figure 2b suggests that the observed structures in the core are part of a torus that constitutes the intersection of the two polar lobes, as depicted schematically in Figure 3. Limb-brightening of the walls of both polar lobes also contributes to the observed structure; Figure 2b shows a morphology expected for an overlapping pair of mostly hollow osculating spheres.

Hony et al. (2001) envisioned a pair of overlapping rings with a symmetry axis very different from the Homunculus as the physical explanation for features that resembled rings or loops in their 8 to $20\ \mu\text{m}$ images. Our $24.5\ \mu\text{m}$ image, which has slightly improved spatial resolution compared to their images, shows one loop-like feature that resembles the brighter of the two rings described by Honny et al. However, our images at shorter wavelengths show that with higher spatial resolution, the illusory loop breaks up into a set of compact knots and incomplete arcs. Thus, our images show that interpreting the complex IR morphology of the inner Homunculus as a pair of smooth rings is less definite than Honny et al. suggest. The geometry they propose cannot be reconciled with the fact that the brightest section of the purported rings is coincident with the optically identified “Weigelt blobs”, whose kinematics indicate that they are indeed equatorial (Davidson et al. 1995). Furthermore, recent results from optical *HST* spectroscopy of η Car contradict Honny et al.’s claim that the orbital axis of the central system has precessed since the Great Eruption in 1843: Kinematics of ionized gas inside the Homunculus indicate that some material ejected around 1890 has the same bipolar axis as the Homunculus (Ishibashi et al. 2001), and reflected spectra of the central star show that its current polar axis is still aligned with the Homunculus (Smith et al. 2001b). Since the putative smooth double-ring structure may be an artifact of insufficient spatial resolution, Honny et al.’s suggestion that tidal interactions after the Great Eruption changed the polar axis of the hypothetical binary system remains unsubstantiated.

Another possible interpretation of the bright IR structures in the core of the Homunculus invokes a toroidal distribution of dust (at ~ 3000 AU from the star), although the torus must have suffered significant disruption. Suppose an initial torus or disk existed around the star, and that stellar wind or ejecta then plowed into this material, as often invoked in hydrodynamic simulations of bipolar nebulae (Frank et al. 1995; Dwarkadas & Balick 1998). Dense knots in that torus would not be accelerated as quickly as material between them, forming the protruding dense knots and more extended arcs seen in our images (note that the knots are all closer to the star than adjacent arcs; see also Figure 3). The dense knots could be pre-existing density enhancements, or perhaps could result from Rayleigh-Taylor instabilities. In either scenario, the knots would be analogous to bright ends of dust pillars often seen in star forming regions, but on a much smaller size scale around η Car. So far, 2-D numerical simulations do not predict such structures, but we expect that they may be seen in fully 3-D simulations. Alternatively, one can imagine more complicated mass-ejections with preferred directions that disrupt the torus. We cannot yet rule out this possibility. Based on our images, we cannot infer the age or exact origin of the equatorial structures; kinematic information is needed. Comparing the distribution of dust emission and ionized gas (for which kinematics are available) may help clarify the inner geometry of the Homunculus.

Our analysis of the new IR images presented here suggests that the bright structures in the core of the nebula are indeed part of a circumstellar equatorial torus or disk, as proposed previously by several authors. This could have important implications for shaping the bipolar Homunculus and its ragged equatorial debris disk. The nature and location of the excess far-IR flux seen in the *ISO* spectrum (Morris et al. 1999) remains unanswered; resolving this dilemma is important because it means that several M_{\odot} of material in the Homunculus may be unaccounted for, which would have important implications for the energy budget

during η Car’s Great Eruption. The temperature map in Figure 2*a* suggests that some of the missing cool dust may actually reside in the polar lobes; we will address this separate problem in a future publication with a more thorough quantitative analysis.

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REFERENCES

- Burrows, C.J., et al. 1995, *ApJ*, 452, 680
- Davidson, K., & Humphreys, R.M. 1997, *ARAA*, 35, 1
- Davidson, K., & Smith, N. 2000, *Nature*, 405, 532
- Davidson, K., Ebbets, D., Weigelt, G., Humphreys, R.M., Hajian, A., Walborn, N.R., & Rosa, M. 1995, *AJ*, 109, 1784
- Dwarkadas, V.V., & Balick, B. 1998, *AJ*, 116, 829
- Frank, A., Balick, B., & Davidson, K. 1995, *ApJ*, 441, L77
- Hackwell, J.A., Gehr, R.D., & Grasdalen, G.L. 1986, *ApJ*, 311, 380
- Hoffmann, W.F., Fazio, G.G., Shivanandan, K., Hora, J.L., & Deutsch, L.K. 1994, *Infrared Phys. Tech.*, 35, 175
- Hoffmann, W.F., Hora, J.L., Fazio, G.G., Deutsch, L.K., & Dayal, A. 1998, in *Infrared Astronomical Instrumentation*, ed. A.M. Fowler, *Proc. SPIE* 3354, 647
- Hofmann, K.H., & Weigelt, G. 1988, *A&A*, 203, L21
- Hony, S., Dominik, C., & Waters, L.B.F.M., et al. 2001, *A&A*, 377, L1
- Hyland, A.R., Robinson, G., Mitchell, R.M., Thomas, J.A., & Becklin, E.E. 1979, *ApJ*, 233, 145
- Ishibashi, K., Gull, T.R., & Davidson, K. 2001, in *ASP Conf. Ser. 242, Eta Carinae and Other Mysterious Stars*, Ed. T.R. Gull, S. Johansson, & K. Davidson (San Francisco: ASP), 71
- Mitchell, R.M., Robinson, G., Hyland, A.R., & Jones, T.J. 1983, *ApJ*, 271, 133
- Morris, P.W., Waters, L.B.F.M., Barlow, M.J., et al. 1999, *Nature*, 402, 502
- Morse, J.A., Davidson, K., Bally, J., Ebbets, D., Balick, B., & Frank, A. 1998, *AJ*, 116, 2443
- Polomski, E., Telesco, C.M., Pina, R.K., & Fisher, S.F. 1999, *AJ*, 118, 2369
- Rigaut, F., & Gehring, G. 1995, *RevMexAA, Ser. Conf.*, 2, 27
- Smith, C.H., et al. 1995, *MNRAS*, 273, 354
- Smith, N., & Gehr, R.D. 2000, *ApJ*, 529, L99
- Smith, N., Gehr, R.D., & Krautter, J. 1998, *AJ*, 116, 1332
- Smith, N., Humphreys, R.M., Davidson, K., Gehr, R.D., Schuster, M.T., & Krautter, J. 2001a, *AJ*, 121, 1111
- Smith, N., Davidson, K., Gull, T.R., & Ishibashi, K. 2001b, in *ASP Conf. Ser. 242, Eta Carinae and Other Mysterious Stars*, Ed. T.R. Gull, S. Johansson, & K. Davidson (San Francisco: ASP), 117
- Westphal, J.A., & Neugebauer, G. 1969, *ApJ*, 156, L45

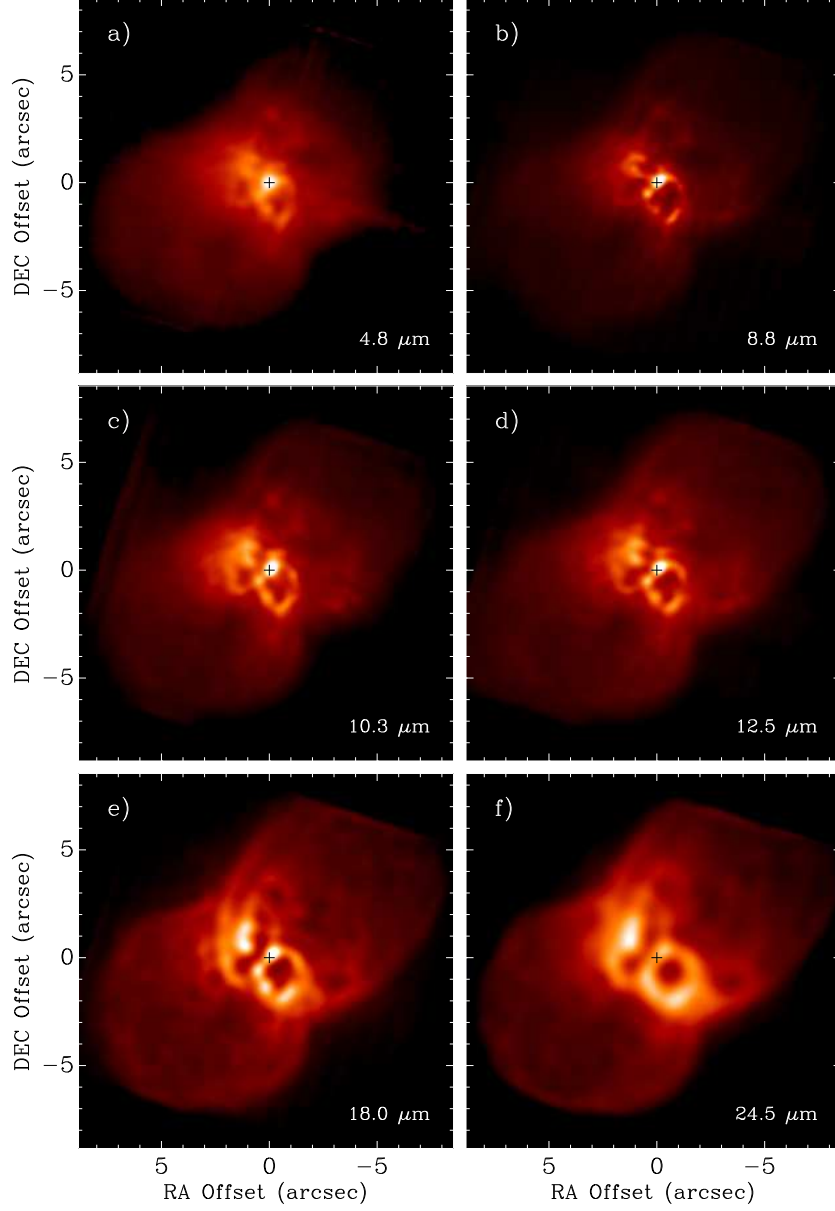


Fig. 1.— MIRAC3/Magellan images of the Homunculus at the indicated wavelengths, shown in false-color using the square root of the observed intensity to accommodate the large dynamic range in the images. The faint streaks at the left edge of panel (c) and the straight termination of the upper-right end of the Homunculus in panels (e) and (f) are artifacts due to the edge of the detector array. In each panel, the black plus-sign marks the position of the central star.

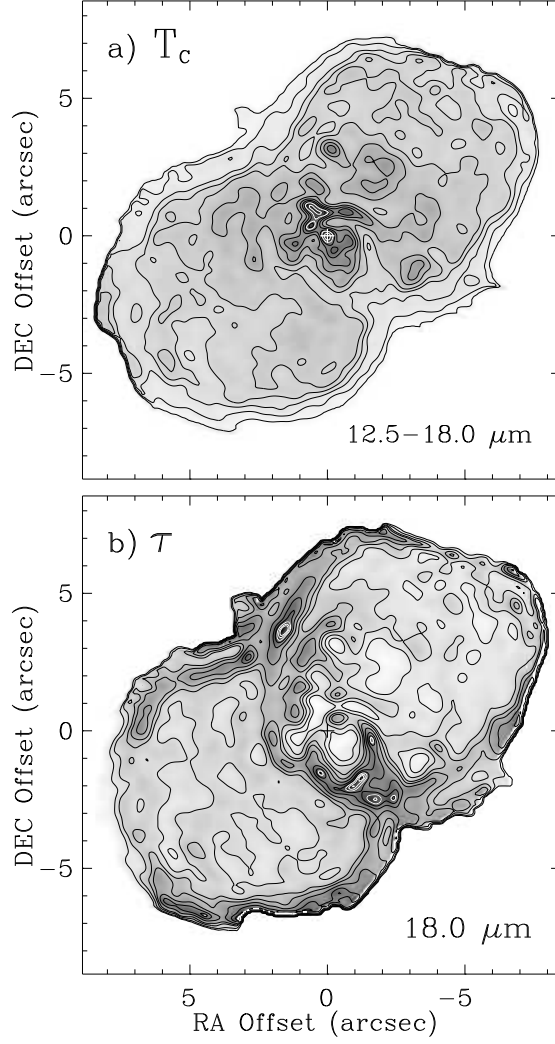


Fig. 2.— (a) Map of the observed dust color temperature resulting from the 12.5 to 18.0 μm flux ratio. Contours are drawn at 120, 140, 160, 180, 200, 240, 280, 320, 360, 400, 450, 550, and 650 K. (b) Corresponding map of emitting optical depth (τ) of dust in the Homunculus at a wavelength of 18 μm . Contours are drawn at values of 0.05, 0.1, 0.2, 0.3, 0.5, 0.7, 1.0, 1.3, 1.6, and 2.0. Contour levels for $\tau > 1$ are white. The plus-sign marks the position of the central star in both panels.

Table 1: MIRAC3 Observations (2001 Aug 8)

λ (μm)	$\Delta\lambda$ (μm)	exp. ^a (sec)	FWHM (arcsec)	standard star
4.8	0.77	646	0.31	γ Cru
8.8	0.88	60	0.35	HD 169916
10.3	1.03	46	0.40	HD 169916
12.5	1.16	46	0.36	HD 169916
18.0	1.80	78	0.42	γ Cru, HD 169916
24.5	1.91	158	0.61	HD 169916

^aTotal on-source exposure time.

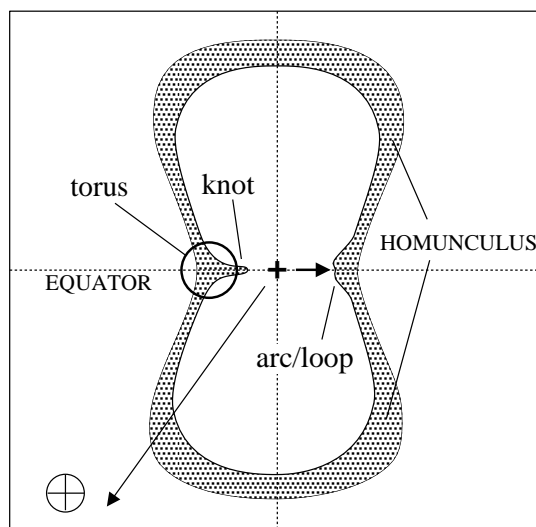


Fig. 3.— Cartoon showing a schematic cross-section of the Homunculus. The region where the two polar lobes meet at the equatorial plane forms a torus. The figure depicts knots that protrude into the nebula in the equatorial plane, as well as arcs that are swept back by stellar wind (the dark arrow). See §3.